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On Aerodynamic Data**

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Quantifying the Effect of Pressure Sensitive Paint On Aerodynamic Data

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ABSTRACT

A thin pressure sensitive paint (PSP) coating can slightly modify the overall shape of a wind-tunnel model and produce surface roughness or smoothness that does not exist on the unpainted model. These undesirable changes in model geometry may alter flow over the model, and affect the pressure distribution and aerodynamic forces and moments on the model. This study quantifies the effects of PSP on three models in low-speed, transonic and supersonic flow regimes.

At a 95% confidence level, the PSP effects on the integrated forces are insignificant for a slender arrow-wing-fuselage model and delta wing model with two different paints at Mach 0.2, 1.8, and 2.16 relative to the total balance accuracy limit. The data displayed a repeatability of 2.5 drag counts, while the balance accuracy limit was about 5.5 drag counts. At transonic speeds, the paint has a localized effect at high angles of attack and has a resolvable effect on the normal force, which is significant relative to the balance accuracy limit.

For low speeds, the PSP coating has a localized effect on the pressure tap measurements, which leads to an appreciable decrease in the pressure tap reading. Moreover, the force and moment measurements had a poor precision, which precluded the ability to measure the PSP effect for this particular test.

NOMENCLATURE

A & B	Stern-Volmer Coefficients
AOA, α	Angle of Attack, degrees
C_d	Coefficient of drag
C_l	Coefficient of lift
C_p	Pressure Coefficient
C_{AF}	Coefficient of Axial Force
C_{NF}	Coefficient of Normal Force
δ_l	Boundary-layer displacement thickness
Δh	Local paint thickness variation
ESP	Electronic Scanner Pressure
K	Stern-Volmer constant
M	Mach number

Re	Unit Reynolds Number, ft^{-1}
P_1	Reference Pressure, psi
P_2	Measured pressure, psi
MDOE	Modern Design of Experiments
NACA	National Advisory Committee for Aeronautics
NASA	National Aeronautics and Space Administration
PSP	Pressure Sensitive Paint
LTPT	Low-Turbulence Pressure Tunnel
UPWT	Unitary Plan Wind Tunnel
x/c	Streamwise distance from leading edge/ chord length
Y/b	Spanwise distance/model span

INTRODUCTION

The pressure sensitive paint (PSP) technique is used to measure the global pressure distribution on wind-tunnel models by coating the article surface with a luminescent paint. When the paint is illuminated by light of appropriate wavelength, the emitted luminescent intensity is inversely proportional to the pressure due to oxygen quenching. The pressure distribution can be obtained from the intensity distribution of the PSP. Details of the theory and applications of PSP can be found in the literature [1-4].

Although the PSP technique becomes an alternative to the classical method of measuring pressure through taps, there are still some aspects that need to be improved. One aspect that has not been fully characterized is the possible intrusive effect of a PSP coating on the aerodynamic flow over a test model. The paint affects the surface finish, thickness and shape of the test article. Paint intrusiveness may not directly affect the pressure measurement, but the surface finish can have an effect on the boundary layer, skin friction, shock location, and drag. Basically, the effects of a PSP coating on pressure and skin friction are directly associated with local changes of flow structures and propagation of the induced perturbations in the flow. The integrated aerodynamic forces may be collectively affected by these local changes.

When flow over a simple aerodynamic model is attached, a quantity to characterize the effect of a PSP coating is a ratio between the boundary-layer displacement thickness δ_l and the local paint thickness variation Δh . For $\delta_l / \Delta h \gg 1$, the external inviscid flow is not altered by the PSP coating. This is a condition under which PSP measurements are normally conducted. However, when the Reynolds number is so large

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that $\delta_l / \Delta h \sim 1$, a PSP coating may directly change the external inviscid flow, particularly near the leading edge of the model.

Several studies have shown that the paint can cause a pressure difference between paint-on and paint-off cases. Engler et al.⁵ reported that pressure coefficients on a PSP painted delta wing model were about 3% higher than that on the unpainted model in transonic regime. Lyonnet et al.⁶ showed that there was a difference in transition location caused by the paint on the wings of an Airbus model. In 1998, Sellers⁷ noticed that on a Dornier Alpha Jet model the painted model had little effect at low Mach numbers, but the paint changed the shock wave position on the wings at Mach number of 0.835.

Other studies have focused on characterization of paint intrusiveness using wind tunnel data. A coating may influence laminar separation bubbles near the leading edge at low Reynolds number and high angles-of-attack. The perturbations induced by a rough coating near the leading edge may enhance mixing that entrains the high-momentum fluid from the outer flow into the separated region. Consequently, the coating causes the laminar separation bubbles to be suppressed. Vanhoutte et al.⁸ reported this effect and found a reduction in drag associated with it. The perturbations of a rough coating could be amplified by several hydrodynamic instability mechanisms such as the Kelvin-Helmholtz instability in the shear layer between the outer flow and separated region and the cross-flow instability near the attachment line on a swept wing. Mebarki's work showed that PSP could cause reduction in lift at high angles of attack with smooth and thin PSP layers at high Reynolds numbers⁹.

Schairer et al.^{10,11} observed that a rough coating on the slats slightly decreased the stall angle of a high-lift wing. He found that the empirical criteria of "hydraulically smooth" and "admissible roughness" based on 2D data were not sufficient to provide an explanation for the observation. Indeed, in 3D complex flows in the high-lift model, the effects of the coating on the cross-flow instability and interactions between boundary-layer and other shear layers, such as wakes and jets, are not fully understood at all. Amer et al.¹² found that the effect of paint on integrated forces and moments were negligible at low Mach numbers on a delta wing model, and at high Mach number on a semi-span arrow-wing model.

This paper describes wind tunnel tests that were conducted to study the paint effects on aerodynamic data and provides an analysis of the results. Two tests were conducted in the Langley Research Center (LaRC) Unitary Plan Wind Tunnel (UPWT), on an Arrow wing model at Mach number 2.4 and on a 65° Delta wing model at Mach numbers 1.8 and 2.16 respectively. Another test was conducted in the LaRC 16' Transonic Tunnel on a proprietary model at Mach number of 0.9. Finally, two tests were conducted at the LaRC Low

Turbulence Pressure Tunnel (LTPT) on the 65° Delta wing model for measurements of forces and moments.

METHODOLOGY

Wind Tunnels

The LaRC Low-Turbulence Pressure Tunnel (LTPT) is a single-return, closed-circuit tunnel that can be operated at stagnation pressures from 0.1 to 10 atmospheres. LTPT is a unique facility that provides flight Reynolds number tests capability for two-dimensional airfoils and a low turbulence environment for laminar flow control studies. The 65° delta wing was tested at LTPT at a Mach number of 0.20, a Reynolds number range of 4-13 million per foot and an angle of attack range of - 2 to 14 degrees. Two separate tests were conducted for force and moment measurements and pressure measurements.

The LaRC 16-Foot Transonic Tunnel (16-Ft TT) is an atmospheric, closed circuit tunnel with a Mach number range of 0.2 to 1.25. The test section of the tunnel is octagonal with a distance of 15.5 ft across the flats. The twin 34-ft diameter drive fans form a two-stage axial flow compressor with counterrotating blades and no stator. Boundary layer control during transonic operation is achieved with a 35,000-hp axial flow compressor that is able to remove up to 4.5 percent of the tunnel flow from the plenum that surrounds the test section. One test was conducted at the 16ft Transonic Tunnel on a proprietary model at a Mach number of 0.9 using S-C FEM paint.

The LaRC Unitary Plan Wind Tunnel (UPWT) is a closed-circuit continuous flow pressure tunnel with two separate test sections that are nominally 4 feet by 4 feet in cross section and 7 feet long. The Mach number range is approximately 1.50 to 2.86 in Test Section 1 and 2.30 to 4.63 in Test Section 2. The stagnation pressure can be varied up to a maximum of approximately 50 psia in Test Section 1 and approximately 100 psia in Test Section 2. Two tests were conducted in UPWT to quantify the paint effect. One test was conducted in Test Section 1 on the 65° delta wing model at Mach numbers of 1.8 and 2.16; the other test was conducted at Test Section 2 on slender arrow wing-fuselage-nacelle model at a Mach number of 2.4.

(<http://wte.larc.nasa.gov/facilities/aerodynamics>)

Models

The 65° Delta wing model, constructed of stainless steel, had an NACA 64A005 airfoil section from the 40-percent chord station to the wing trailing edge. The right wing was

instrumented with 54 pressure taps placed in three chord-wise rows on the upper surface. The model was instrumented with a force and moment balance. Figure 1 shows the model schematic and target locations.

A 1.675%- scale Arrow Wing model was tested to determine the effect of PSP on the longitudinal force and moment characteristics of a slender wing-fuselage configuration at supersonic speeds. Figure 2 shows the slender narrow wing-fuselage-nacelle model. Model length was 52.74 inches, model span was 25.794 inches, and model height was 5.00 inches. This model was not instrumented with any surface static pressure taps.

A detailed description of the proprietary model that was tested at 16' Transonic Tunnel cannot be presented.

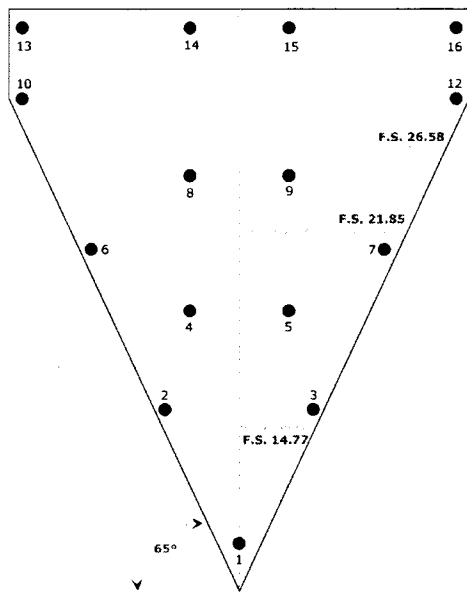


Figure 1. Sketch of 65° Delta Wing Model.

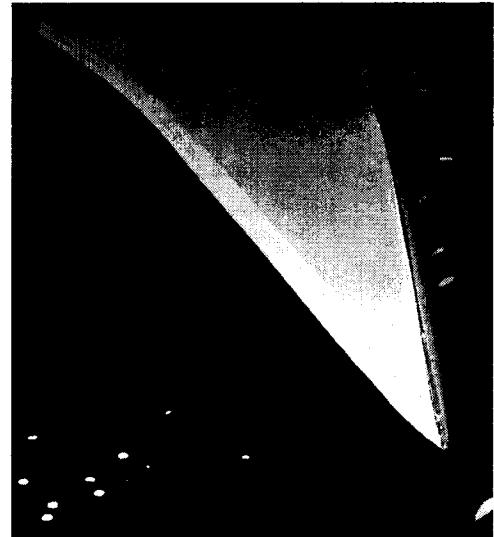


Figure 2. Arrow Wing Model.

Paints

PSP Paint

For all of the tests, the upper surfaces of the models were painted with PSP developed by NASA Langley Research Center or with commercially available paints. A total of five different paints were used, each consisting of either a two-coat paint that consisted of a white base coat and the topcoat of the active pressure sensitive paint or a single-coat paint that had the base and top coat combined into a single application formulation. Table 1 provides a summary of each type of paint tested and where it was used. After every paint application was completed, the paint thickness and paint roughness were measured at various locations along the wing surface. As shown in the table the average paint thickness varied from 10 to 63.5 μm depending on the paint type. The reported values are an average of 10-15 measurements although some variations occurred across the model surface within a single application. The roughness also varied considerably (depending on the paint) from 0.28 to 1.18 μm . The response characteristics of each paint are also listed.

Paint	User*	Thickness (μm)	Roughness (μm)	Stern-Volmer Constant (psia^{-1})	Optimal Pressure (psia)	Pressure Sensitivity (psia^{-1})	Temperature Sensitivity % / C
2-Step FEM	LaRC	63.5	0.28–0.39	0.40	2-3	0.053	-1.3
S-C FEM	LaRC	25-30	0.38	0.40	2-3	0.053	-1.3
FIB	ARC/AEDC	15	0.78-1.18	0.60	1-2	0.055	-0.8
UniFIB	ARC/GRC	20	0.90	0.60	1-2	0.055	-0.8
Uni-Coat	ISSI	20	0.45	0.072	12-14	0.033	-1.7

*User: LaRC = Langley Research Center, ARC = Ames Research Center, AEDC = Arnold Engineering Development Center, GRC = Glenn Research Center, ISSI = Innovative Scientific Solutions, Inc.

Table 1. Pressure sensitive paint characteristic summary.

The NASA Langley Research Center PSP was composed of poly-ti fluoroethylmethacrylate-co-isobutylmethacrylate (FEM) as the binder, lacquer thinner solvents, and platinum tetra (pentafluorophenyl) porphrine as the luminophor. The single-coat paint included the extracted pigment from the commercially available white base coat (used in the two-coat paint) in the formulation. The commercially available PSP's included similar two-coat and single-coat paints based on poly-heptafluoro-n-butyl methacrylate-co-hexafluorisopropyl methacrylate as the binder. The final commercially available paint was another single-coat formulation that has a proprietary binder. All of the formulations represent the most commonly used paints in the PSP community.

Paint	Binder	Luminophor
2-coat FEM and S-C FEM	poly-ti fluoro- ethylmethacrylate-co- isobutylmethacrylate	platinum tetra (pentafluoro- phenyl) porphrine
FIB and UniFIB	poly-heptafluoro-n- butyl methacrylate-co- hexafluorisopropyl methacrylate	platinum meso- tetra (pentafluoro- phenyl) porphrine
Uni-Coat	proprietary	

Table 2. Pressure sensitive paint compositions.

The models were thoroughly cleaned before a spray application of the primer or the PSP paint. While painting the model, clean air was gently (25-40 psi) blown through the model pressure taps to prevent paint from clogging the taps. Most of the paints were applied using standard commercial spray equipment. The Uni-coat paint was applied directly from the supplied spray can much like household spray paints. The application process of the PSP involved shaking the container for 2-4 minutes and spraying uniformly over the model surface, until a sufficient PSP layer had developed (providing a uniform medium shade of pink). The paints dried very quickly to a smooth hard surface. On a few occasions, the paint was sanded with 1000 grit wet-or-dry sandpaper to bring the thickness and roughness to within the specifications of the paint.

The instrument used to measure the thickness of the primer and PSP coating utilized the eddy current test method. Measurements were made at between 10 and 15 locations on the wing surface. Surface roughness was measured at the same general locations as the thickness measurements by reading the average peak height of the roughness over the measured distance.

RESULTS

Supersonic Testing at UPWT

Two tests were conducted in the UPWT Test Sections 1 and 2 on different models at different times. The slender arrow wing-fuselage model was tested at a Mach number of 2.4 and Reynolds number of 4.0 million per foot, respectively. The angle of attack was -2 to +6 degrees. This test was conducted in Test Section 2. The test was a force and moment test and no PSP image was taken. The PSP was applied four times and all the necessary data were acquired according to Modern Design of Experiment (MDOE)¹³⁻¹⁵. Figures 3-6 present sample results of the test, which shows no paint effect on the C_d , C_l and pitching coefficient for the two-coat FEM paint.

Additionally, the 65° delta-wing model was tested at UPWT Test Section 1 to quantify the PSP effect on the aerodynamic data. The test was carried out using several different types of paint; NASA Langley single-coat FEM, and two commercially available paints, FIB and UniFIB. This test had two parts. The first was the PSP effect on force and moment measurements and the second was the effect on the measured pressure distributions. It was found that the average thickness of S-C FEM, FIB, and UniFIB were approximately 25, 15, and 20 μm , respectively. Moreover, the average roughness of S-C FEM, FIB, and UniFIB were 0.38, 0.98, and 0.9 μm .

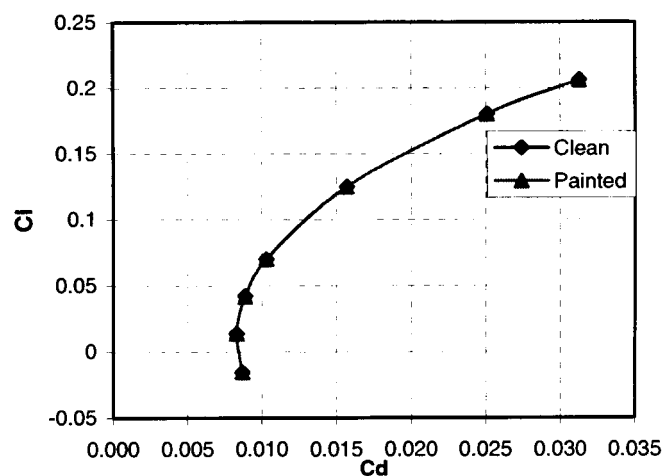


Figure 3. The difference of C_l versus C_d of painted and clean wing in UPWT for Mach = 2.4, on the Arrow Wing Model.

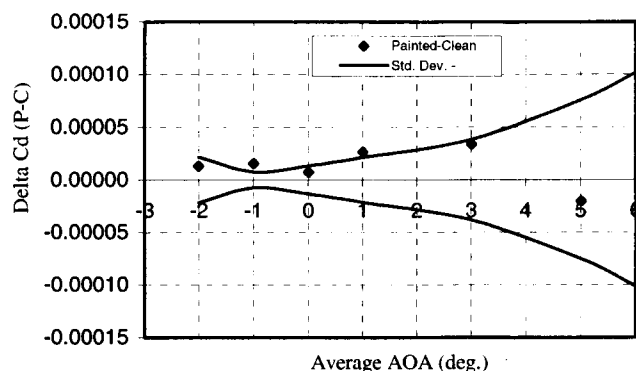


Figure 4. The changes in C_d versus AOA in UPWT at $M=2.4$.

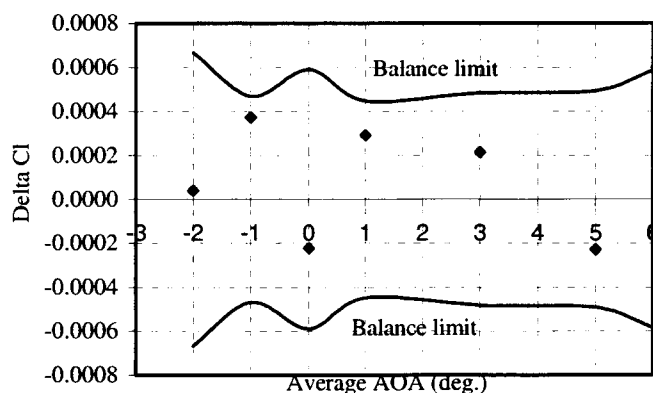


Figure 5. The changes in C_l versus AOA at $M=2.4$ for the Arrow Wing Model.

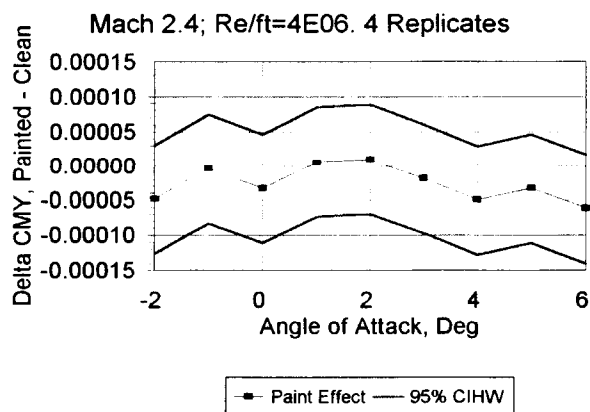


Figure 6. The effect of PSP on the Pitch Moment at UPWT for Four Replicates.

For the force and moment measurement test, S-C FEM and UniFIB had been applied to the 65° delta wing. The results shown in Figures 7 and 8 are for the axial force for S-C FEM and UniFIB at $M=1.8$ and 2.16 respectively, the paint effects are within the balance tolerance specifications. The calculated drag coefficients for both paints are within the test drag limits,

as shown in Figures 9 and 10. Figures 9 and 10 also show the balance accuracy limits, the test repeatability limits, and the difference between paint-on and clean wing for C_d . The S-C FEM and UniFIB paint effect is not distinguishable from zero within the 95% confidence level based on this model and the specific test condition. The paint-on and -off the wings indicating that the paint effect on the drag coefficient is not resolvable.

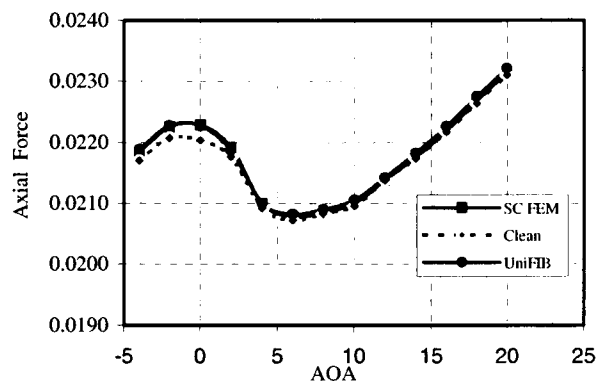


Figure 7. The effect of PSP on the Axial Force in UPWT $M=1.8$ for S-C FEM & UniFIB.

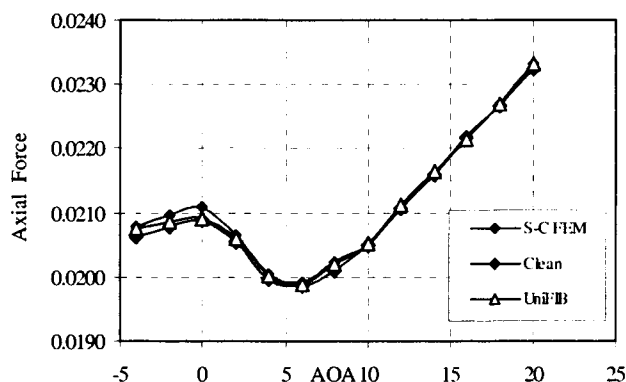


Figure 8. The effect of PSP on the Axial Force in UPWT $M=2.16$ for S-C FEM & UniFIB.

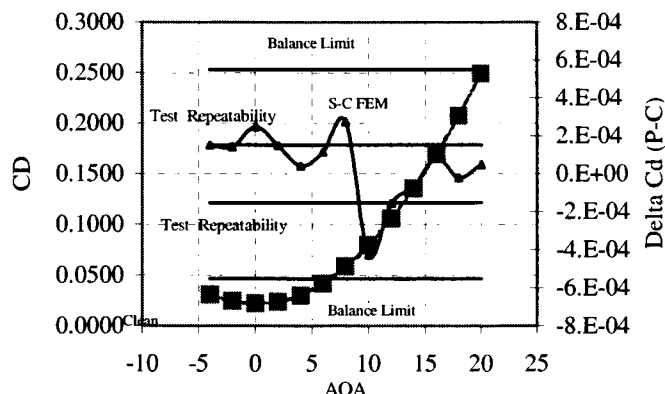


Figure 9. The effect of S-C FEM on the C_d at UPWT $M=1.8$.

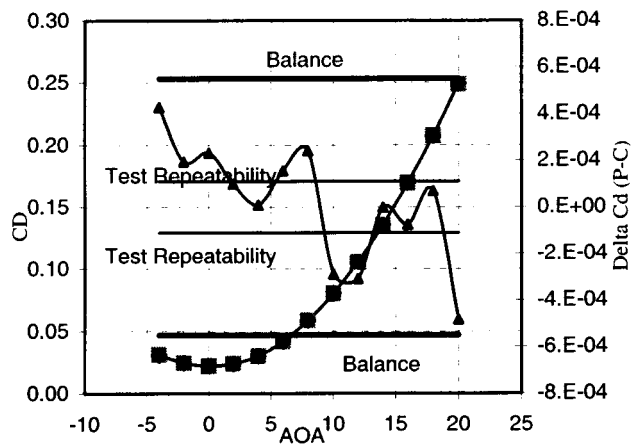


Figure 10. The effect of UniFEB on the C_d at UPWT $M=1.8$.

For the Pressure distribution measurement test, S-C FEM and FIB had been applied to the 65° delta wing. Figure 11 compares C_p of three average three clean and paint-on runs for the S-C FEM for $M=1.8$ and $AOAs = 16$. From the figure, it was difficult to distinguish the difference between clean and painted wing. Similar results were found when testing the FIB paint. Therefore, a better method to evaluate the difference was to subtract the paint-on from the clean data values. For $M=1.8$, $AOA = -2$ to 18 , $\beta=0.0$, as shown in Figures 12A and 12B, the effect of the S-C FEM and FIB on C_p at $x/c=0.3$ and 0.6 were within the allowed tolerance of ESP specifications. However, at $x/c=0.8$ with high angle of attack, the difference between the clean and painted wing fall outside of the ESP specified tolerance show figure 13A and 13B. Figure 14 show a typical histogram of S-C FEM and FIB for $M=2.16$ with PSP errors with a Gaussian probability distributions.

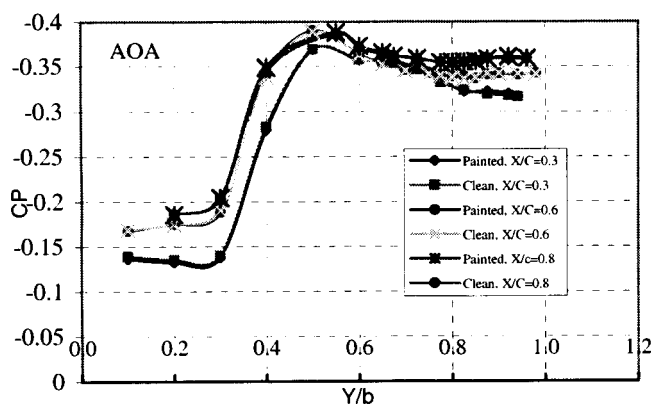


Figure 11. The effect of S-C FEM PSP on the C_p at UPWT $M=1.8$ at $AOA=16.0$.

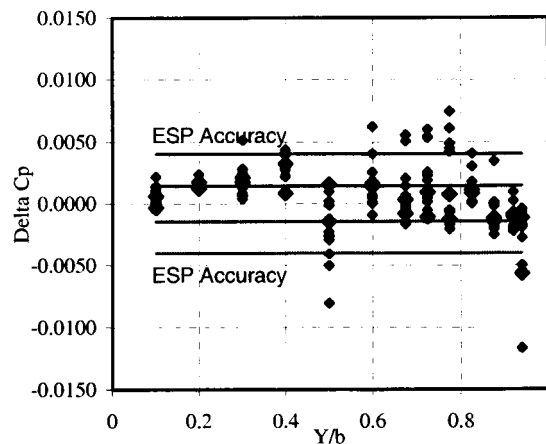


Figure 12(a). The difference between S-C FEM PSP and clean wing of C_p at UPWT @ $M=1.8$ at all AOA.

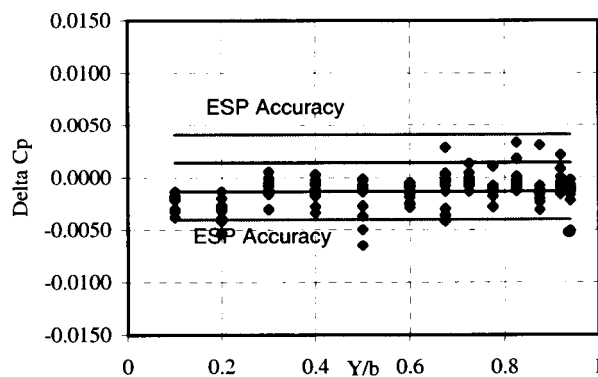


Figure 12(b). The difference between FIB PSP and Clean Wing of C_p at UPWT at $M=1.8$ at all AOA.

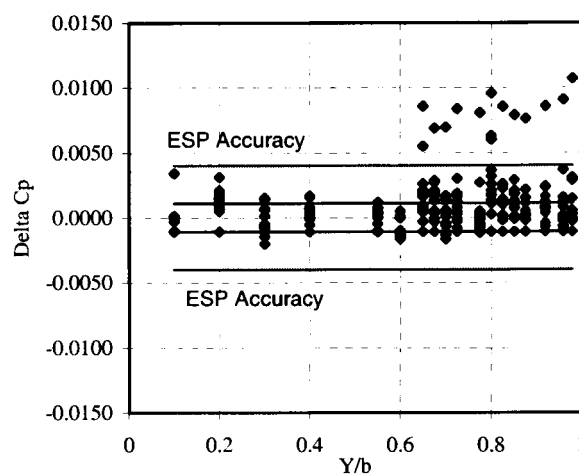


Figure 13(a). The difference between S-C FEM PSP and clean wing of C_p at UPWT at $M=1.8$, $\beta = -4$ at all AOA.

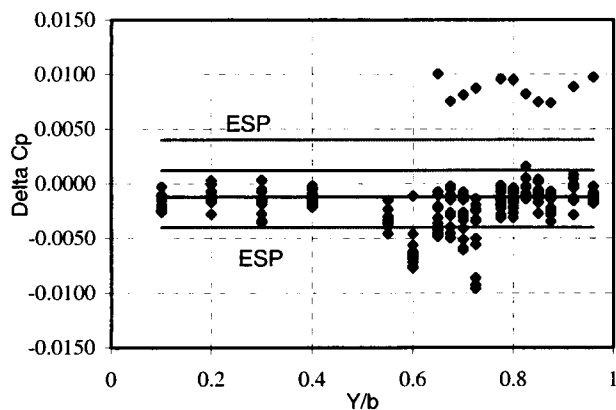


Figure 13(b). The difference between FIB PSP and clean wing of C_p at UPWT @ $M=1.8$ at all AOA.

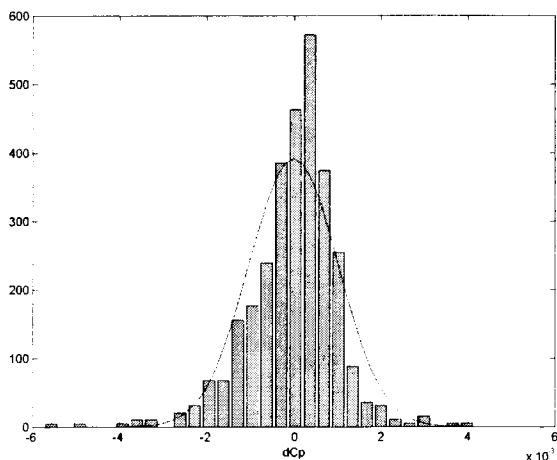


Figure 14. Histogram of FIB PSP Errors With a Gaussian Probability Distribution, $M=2.16$.

Transonic Testing at 16' Transonic Tunnel

A paint intrusiveness test was conducted at the 16' Transonic by comparing several runs with and without paint at the same test conditions. The results of that test are proprietary information; therefore, the data are shown without scales on all figures related to that test.

Several tunnel runs were completed before applying the paint to obtain all the reference clean runs. The test condition was at Mach of 0.90 and low angles of attack. The Single-Coat FEM was applied to the upper surface of the model. The average paint thickness was about $25 \mu\text{m}$, and the roughness was about $0.38 \mu\text{m}$.

Figures 15 and 16 display the coefficients of the normal force and lift for two clean and two paint-on runs at the same test conditions, respectively. There are two lines that are defined as the upper and lower limits of the balance accuracy for this test and have been calculated from data quality runs. There was a noticeable difference between clean and paint-on runs

for the normal force under these test conditions in Figure 15. However, as shown in Figure 16, the coefficient of lift and coefficient of drag were within the limit of the balance at low angles of attack, but for high angles of attack were outside the limits of the balance. Moreover, the difference in drag coefficient data was analyzed and the difference between the clean and paint-on is within the balance limits, as shown in Figure 17.

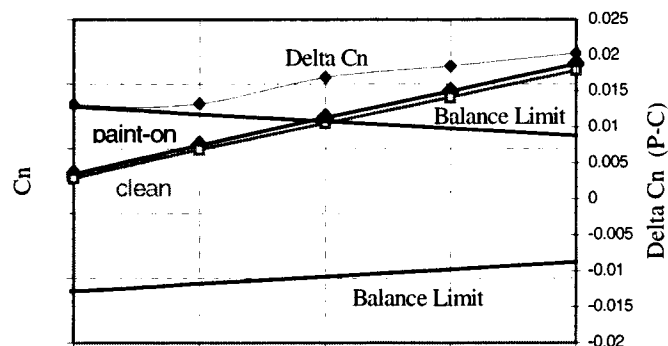


Figure 15. Transonic Test at $M=0.90$, the difference in Normal Force between Clean and S-C FEM.

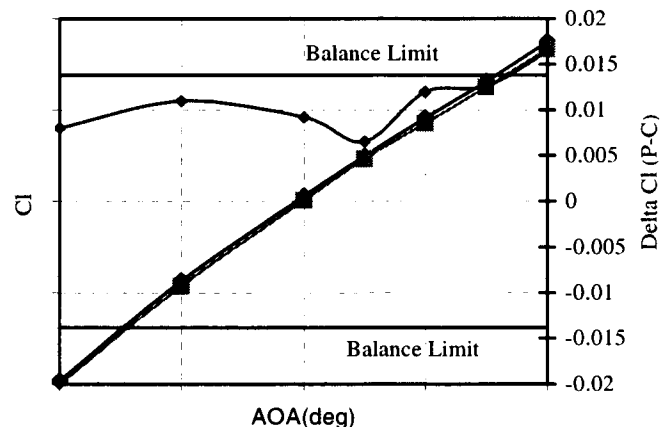


Figure 16. Transonic Test at $M=0.90$, the difference in lift coefficient between clean and painted (S-C FEM).

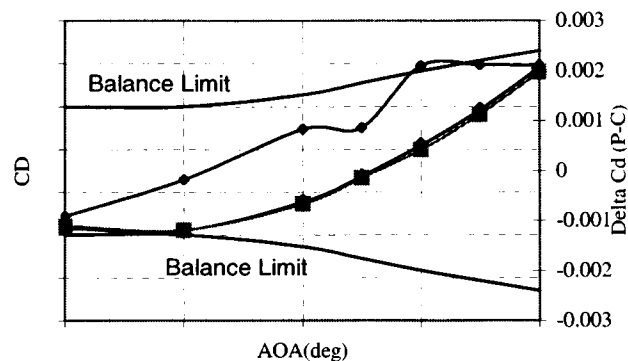


Figure 17. Transonic Test at $M=0.90$, the difference in drag coefficient between clean and painted (S-C FEM).

Other data was collected and evaluated for paint intrusiveness on the pressure coefficient. Figure 18 presents results from back-to-back paint-on runs and its coefficient of pressure limits for a specific pressure tap, but the analysis was conducted for several pressure taps that were located in difference flow regimes. Figure 19 compares the clean and paint-on runs for the pressure tap data. It seems that at high angle of attack there is flow separation or shock development that makes the tap data lie outside the limits. The paint-on pressures are similar to clean wing at a low angle of attack and virtually impossible to see any difference. However, for high angle of attack there was a noticeable difference.

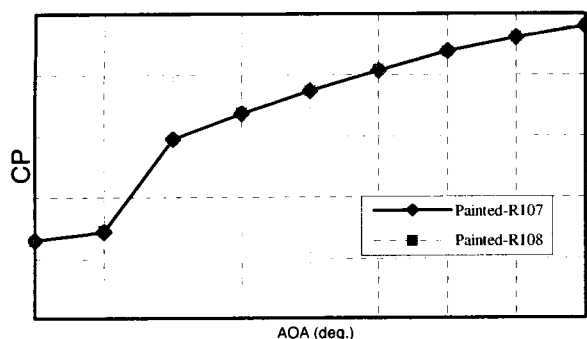


Figure 18. Transonic Test at $M=0.90$, the difference in C_p Back-to-Back with paint (S-C FEM).

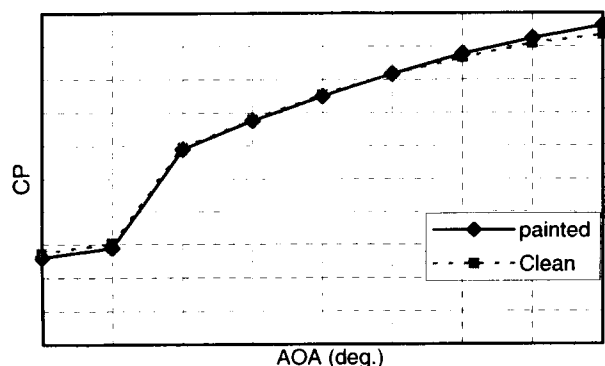


Figure 19. Transonic Test at $M=0.90$, the difference in C_p between Clean and painted wing.

Low Speed Testing at LTPT

A low speed force and moment test was conducted using the 65° delta wing in the LTPT facility. The objective of this test was to characterize the effect of PSP on drag and lift coefficients. The MDOE pre-test analysis suggested that five paint applications would be needed to quantify the effect of the paint with a desired precision level. This method was time-consuming because eight hours were required to apply

and cure the paint. However, each application represented only one degree of freedom to describe the effect of a change in paint state (paint on to paint off). Multiple paint-state changes were required in order to produce enough degrees of freedom to quantify both the main paint-state effect and the uncertainty in estimating that effect. The average thickness for the paint was 2.5 mils and the average roughness was 7 μ -in. The test conditions were Mach 0.20, Re from 4 to 13 million, and angle of attack from -2 to 14 deg. The data was acquired at constant Mach and variation of Re and AOA for five repeated paint applications. For each paint application, there were five replicate data sets. Therefore, for each AOA position obtained a total of 25 data points were processed and analyzed. Figure 20 shows the drag coefficient vs. the lift coefficient for both painted wing and clean wing for Mach 0.2 and Re of 13 million for five replicates. It was difficult to differentiate the paint and clean wing data for this condition. It appears that the PSP had no significant effect. To verify that, a closer look at the data was necessary. The calculated differences of C_d for painted and clean wing as a function of AOA at different Re numbers were plotted in Figure 21 along with the standard deviation for each measurement. It was reasonable to conclude that the PSP had no effect on the coefficient of drag. Similar results were obtained for coefficient of lift and all the moment components.

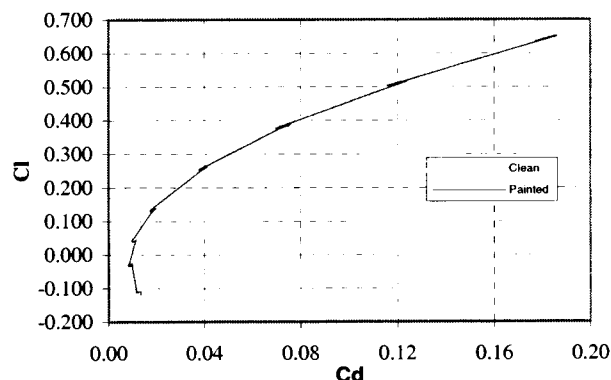


Figure 20. Low Speed Testing at LTPT, drag polar for clean and painted (Two-coat FEM) at $M=0.20$.

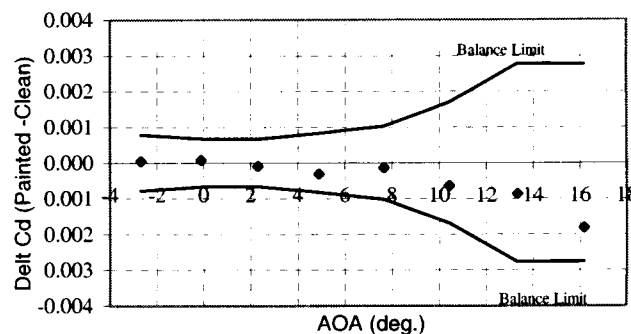
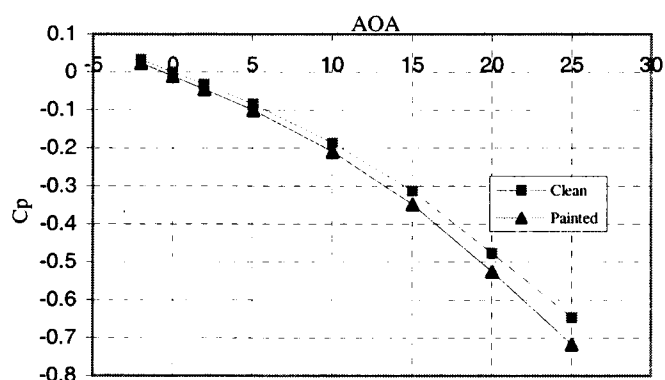
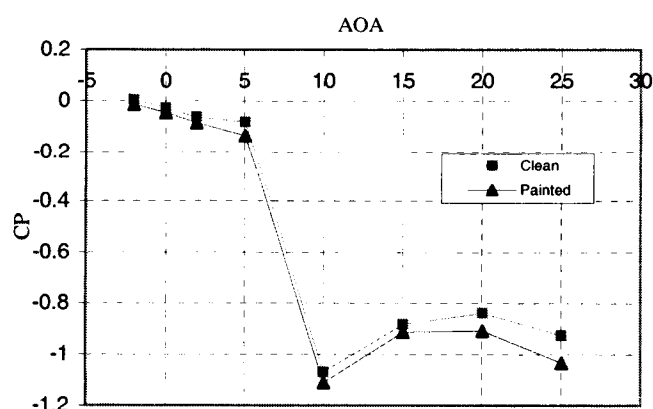


Figure 21. The difference between painted FEM and clean runs.

A surface pressure test was conducted at LTPT on the same 65° delta wing model to continue the characterization of the PSP on pressure distribution. This test was under a time constraint from the facility and the issue of multiple-paint applications had to be resolved. It was decided that for this test, one paint application would be used to acquire all the necessary data. The test conditions for this entry were M at 0.20-0.34, Re at 4-13 millions, and AOA from -2 to 25 deg. By adding the PSP to the model, it was noticed that there was a reduction in C_p tap values for all three rows of taps. Figures 22A and 22B display C_p as a function of AOA at Mach of 0.25 and Re of 10 millions for a specified pressure tap from each row on the model.



(a)

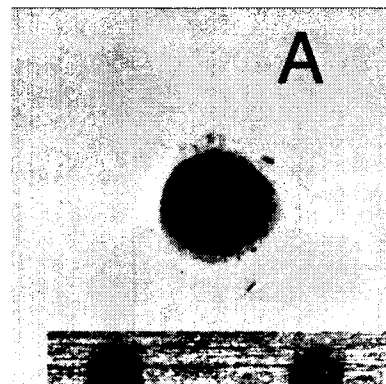


(b)

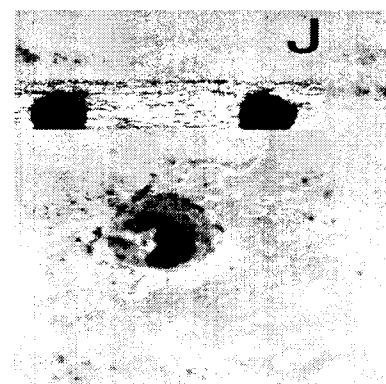
Figure 22. The coefficient of pressure for FEM painted wing and clean wing for Different Taps Locations.

Apparently paint around the taps influences the behavior of the flow around the taps. A study was carried out to obtain close-up images of the taps. Figure 23 shows example images of the taps with PSP applied; tap A was clean and tap J was half clogged, and there were a great deal of paint irregularities

around that tap. These displayed results displayed were unexpected trends because the integrated force and moment data did not show a paint effect in the earlier tests. The reduction in C_p may be due to the localized effect of the paint, but when the integrated force was calculated over the painted surface, the effect was insignificant. Painting a model with PSP is an art that requires certain skills, so that the paint application will not influence the aerodynamic results.



Good tap



Bad tap

Figure 23. Painted tap profile of good tap and bad tap.

An accurate static surface pressure distribution is particularly important for the PSP technique because the PSP image processing requires an in-situ calibration

CONCLUSIONS

The PSP effects on the integrated aerodynamic forces on the two different models at different test conditions at both the LTPT and UPWT are very small over certain ranges of Reynolds number, Mach number and AOA. This is mainly because the tested PSP developed by NASA Langley produces surface roughness that is even smaller than the clean wing. In low-speed testing at LTPT, the differences of the coefficients of lift, drag and other components between the paint-on and

clean models are within the error bounds of measurements by balances. However, an appreciable reduction of the pressure readings in some pressure taps was found on the paint-on model. This may be caused by local topological changes around the taps produced during the painting process. Although this localized effect on pressure taps does not significantly affect the integrated forces, it may lead to an error in in-situ PSP calibration when pressure tap data is used as standard values. Similarly, the supersonic speed testing at UPWT did not show any significant paint effects on the coefficients of lift, drag and other components.

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